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MEMBRANE HUMIDITY CONTROL INVESTIGATION

(TASK ORDER NO. 180)

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SECTION I
PROGRAM SUMMARY

PURPOSE

The purpose of the membrane humidity control program (Task Order No. 180) was to obtain basic performance data on a hollow fiber membrane unit that removes water vapor from a breathing gas loop by diffusion. With this approach no coolant or vapor condensation is required and very low outlet dew points are possible.



SCOPE

The membrane water deaerator program consisted of three tasks. First, a hollow fiber membrane unit made of cellulose acetate was tested to determine the permeability to gas and water vapor. Using the data obtained, an analysis was performed to determine a configuration and preliminary design for a flight unit. Finally, the test and analytical results were documented in a final report. By direction of NASA, testing was halted before any definitive performance data were obtained.



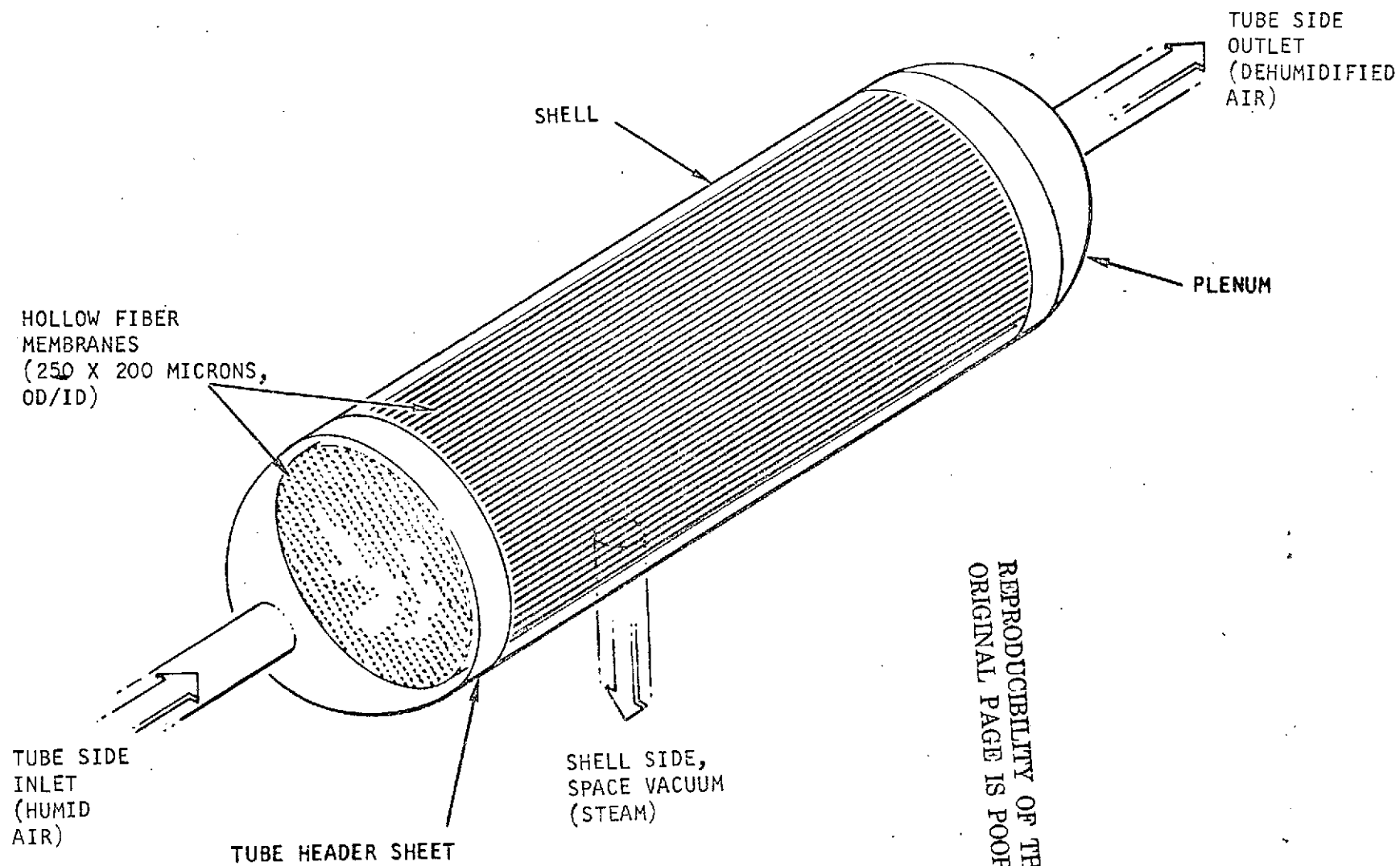
INTRODUCTION

Semi-permeable membranes are thin solid films through which different molecular species diffuse at different rates. Thus, they are potentially applicable to many different mass transfer separation processes as well as phase separation processes in zero-g. Previously, these membranes were fabricated in flat sheets; the flat sheets presented a major obstacle to the full utilization of semi-permeable membranes. A large amount of structure is required to hold flat membranes and a seal is required around both sides of each flat sheet. In addition, each sheet must be supported in order to maintain even a moderate pressure differential (or driving force) across the flat, thin surface.

Recently, semi-permeable membranes have been developed in the form of very small (30 to 250 microns) hollow fibers. These hollow fibers are essentially tubes and, because of their small diameter to thickness ratio, can withstand relatively high pressures. This configuration solves the flat sheet problem of supporting high differential pressures across thin films. A large number of these tubes can be epoxied together at each end of the flow length. Finally, the hollow fibers and epoxied ends are inserted into a metal or polymeric tube, which contains manifolds at each end and an exit port along the tube. The final conceptualized configuration, shown in Figure 1-1, is similar to a single pass tube and shell heat exchanger. Thus, with the emergence of a technique to make hollow fiber type semi-permeable membranes, a lightweight unit can be designed to withstand high pressures and yield higher mass transfer areas than are obtainable with flat sheet membranes. This hollow fiber type of unit is the one used in the current program.

Referring to Figure 1-1, air containing water vapor enters the inlet plenum and flows through the hollow fiber. During passage down the length of the tube, the water vapor permeates (diffuses) through the membrane material due to the water vapor partial pressure difference between the inside and outside surface of the membrane. Permeation of oxygen and nitrogen is negligible, these gases continue down the tube and flow out of the unit and back to the system, while the water vapor flows out to space vacuum.





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Figure 1-1. Membrane Unit Configuration

SUMMARY OF RESULTS

Using available permeability data for cellulose acetate, a preliminary design was made of a dehumidifier unit that would meet the following problem statement. This problem statement is based on maintaining a comfortable environment in the recirculating gas loop of an EVLSS.

TABLE 1-1
DEHUMIDIFIER PROBLEM STATEMENT

Oxygen Loop Parameters	Max. Sustained Heat Load Condition	Min. Heat Load Condition
Inlet Total Flow, lb/hr	16.0	16.0
Pressure, psia	8.0 \pm .15	8.0 \pm .15
Inlet Temperature, °F	110 min.	72 max.
Inlet Dew Point, °F	94	72
Inlet H ₂ O Flow, lb/hr	0.903	0.47 max.
Outlet Temperature and Dew Point, °F	50 max.	35 min.
H ₂ O Condensate Rate, lb/hr	0.728	0.356
Pressure Drop, in. H ₂ O	2.8 max.	2.8 max.

In addition, the maximum pressure drop across the dehumidifier will be less than 1.5 inches of water.

The unit that meets the problem statement is shown in Figure 1-2. The controlling parameter in the design was the allowable pressure drop of 1.5 inches of water, this resulted in a unit with a short flow length and a large frontal area. Permeability values used in the design were reported literature values, the test program was halted before these values could be confirmed.

Some of the characteristics of the unit are given in Table 1-2.

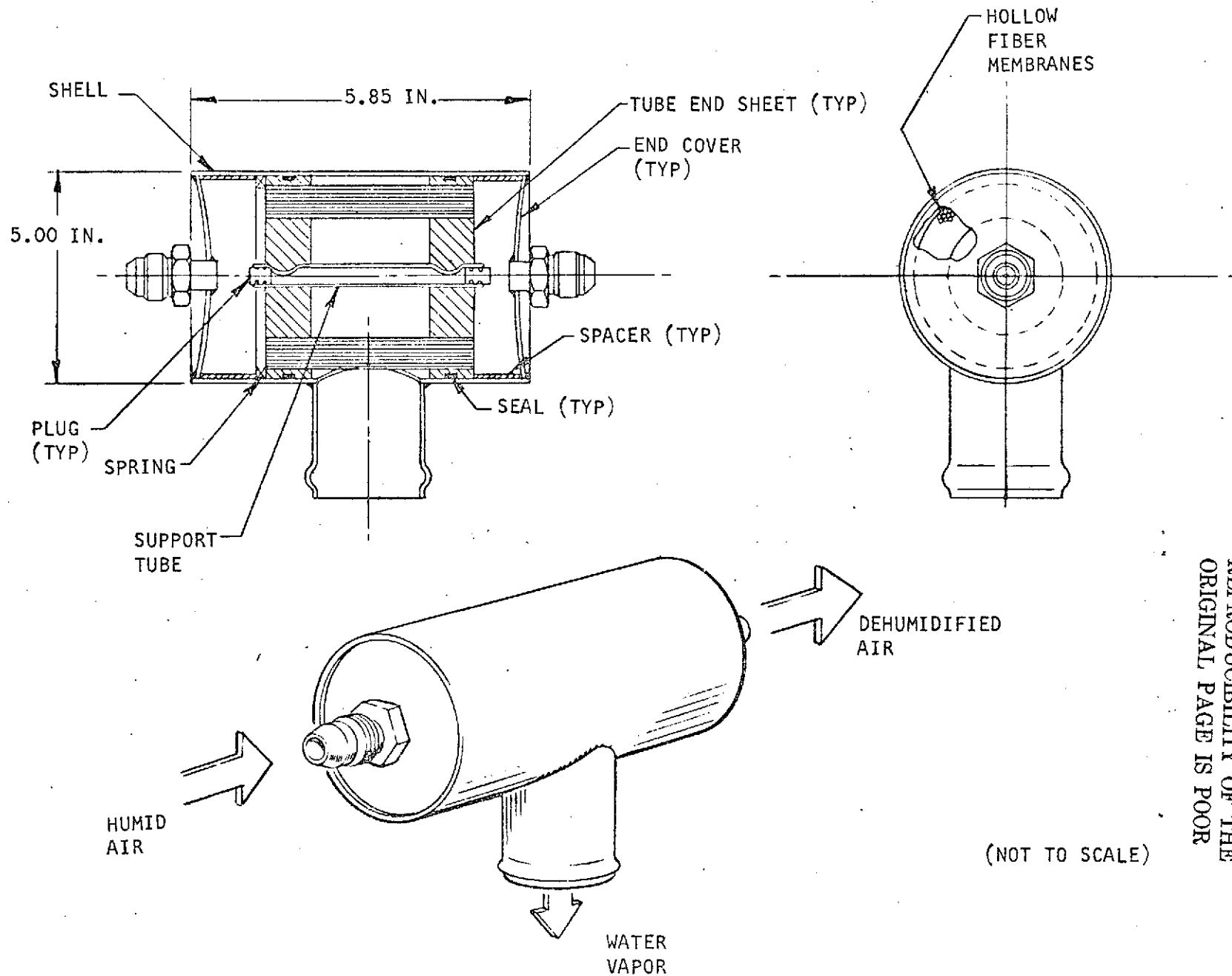
TABLE 1-2
DEHUMIDIFIER UNIT CHARACTERISTICS

Membrane Material	cellulose acetate
Envelope (excluding fittings)	5.00 in. dia x 5.85 in.
Weight	3.2 lb
Active area	147 ft ²
Tube size	250 O.D. x 200 I.D., microns





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Figure 1-2. Membrane Dehumidifier

RECOMMENDATIONS

The following program plan is recommended for the next phase of work on the membrane dehumidifier. It is based on the results obtained to date and proposes the development of a unit for a specific EVLSS problem statement.

1. Program Plan

a. Laboratory Tests

Performance tests will be conducted to determine the permeability of the cellulose acetate unit at various inlet dew points, flow rates and temperature. This will be followed by a hundred hour life test, a post-performance gas permeability and burst test, and fiber strength tests.

b. Analysis and Design

Analyses will be performed to evaluate the data obtained with the laboratory unit. This will then be used to design a unit to a specific problem statement.

c. Fabrication and Verification Tests

A unit will be fabricated and tested to verify its performance. Testing will include the effect of inlet conditions (pressure, temperature, gas flow rate and dew point) on the amount of water removed. In addition, a vibration test will be conducted to verify the integrity of the unit.

d. Documentation

Results of the analytical, design and test effort will be documented in a Final Report. In addition, recommendations will be made for the follow on effort leading to a qualified unit.



SECTION 2
MEMBRANE TEST PROGRAM

Several possible available hollow fiber materials were evaluated for use as a dehumidifier. The most promising materials found were cellulose and cellulose acetate as shown in Table 2-1. These materials have extremely high permeability constants for water vapor and, thus, would result in relatively small units. The wide range of permeability values, for a given material, shown in Table 2-1 is due to using material made by various manufacturers and using various testing techniques. Because the cellulose acetate material has a generally higher permeability constant and has slightly better structural characteristics than cellulose, it was selected for testing. The characteristics of the test unit are:

Tube size, microns	250 O.D. x 200 I.D.
Mean surface area, ft ²	12.2
Number of fibers	9640
Active tube length, inches	6.5

The laboratory test unit was modified by removing the shell, placing the unit in a special test fixture to hold the tube end sheet and the air plenums. In addition, special plenums made of stainless steel were used so that a load could be applied to the "O" ring to seal off and prevent leaks from the plenum to vacuum.



TABLE 2-1

FIBER PERMEABILITY AND STRENGTH CHARACTERISTICS

Material	Permeability (*) at 25°C			Tensile Strength at Yield psi	Elongation At Yield Percent
	H ₂ O	O ₂	N ₂		
Cellulose	1350 - 13,500 ⁽¹⁾ 33,000 ⁽²⁾	0.0012-0.03 ⁽⁶⁾	0.003-0.0096 ⁽⁶⁾	---	---
Cellulose Acetate	11,200 ⁽¹⁾ 410 - 54,000 ⁽²⁾ 1500 - 10,600 ⁽³⁾	0.4-0.78 ⁽³⁾	0.16-0.5 ⁽³⁾	---	---
Polymethyl Pentene	850 - 960 ⁽⁴⁾	27 ⁽⁴⁾	6.5 ⁽⁴⁾	4 x 10 ³ ⁽⁴⁾	2 ⁴
Polyethylene Terephthalate	130 - 230 ⁽³⁾ 282 ⁽⁵⁾	0.03 ⁽³⁾	0.005 ⁽³⁾	1.3 x 10 ⁴ ⁽⁷⁾	3-4 ⁽⁷⁾

* Units (cm³(STP) - cm/cm² - sec - cm Hg) X 10¹⁰

- (1) P.M. Hauser and A.D. McLaren, Industrial and Engineering Chemistry, 40, 112 (1948).
- (2) R.M. Barrer, Diffusion in and Through Solids, Cambridge University Press, London, 1951, p. 394.
- (3) A. Lebovitz, Modern Plastics, 43, 139 (1966).
- (4) International Chemical Industries, Technical Bulletin, No. 252.
- (5) M. Salame, Problem Solving with Plastics Symposium, NACE, 1971, p. 82-86.
- (6) 1971-1972 Modern Plastics Encyclopedia, p. 622.
- (7) L. Amborsk and D.W. Flier, Industrial and Engineering Chemistry, 45, 2290 (1953).



TEST SYSTEM DESCRIPTION

The purpose of the test program was to obtain basic performance data on a hollow fiber membrane unit when used as a dehumidifier. A test system was assembled, using nitrogen as the test gas, that would condition the inlet gas to the membrane unit to the desired pressure, temperature and water vapor content. The membrane unit itself was placed in a large vacuum chamber, which was connected to a high capacity vacuum pumping system. Figure 2-1 is a picture of the test setup, Figure 2-2 of the test unit and Figure 2-3 is a schematic of the test setup. Water vapor content of the gas stream was determined by visually observing (either automatically or manually) the formation of water or ice on a cooled mirror and noting the gas stream temperature and pressure at this time. The test components shown in Figure 2-3 are described in Table 2-2.



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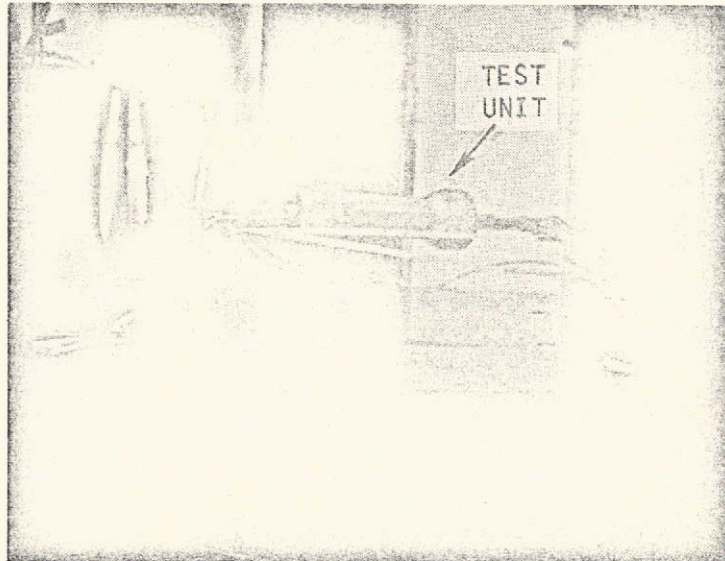


Figure 2-1. Dehumidifier Test Setup



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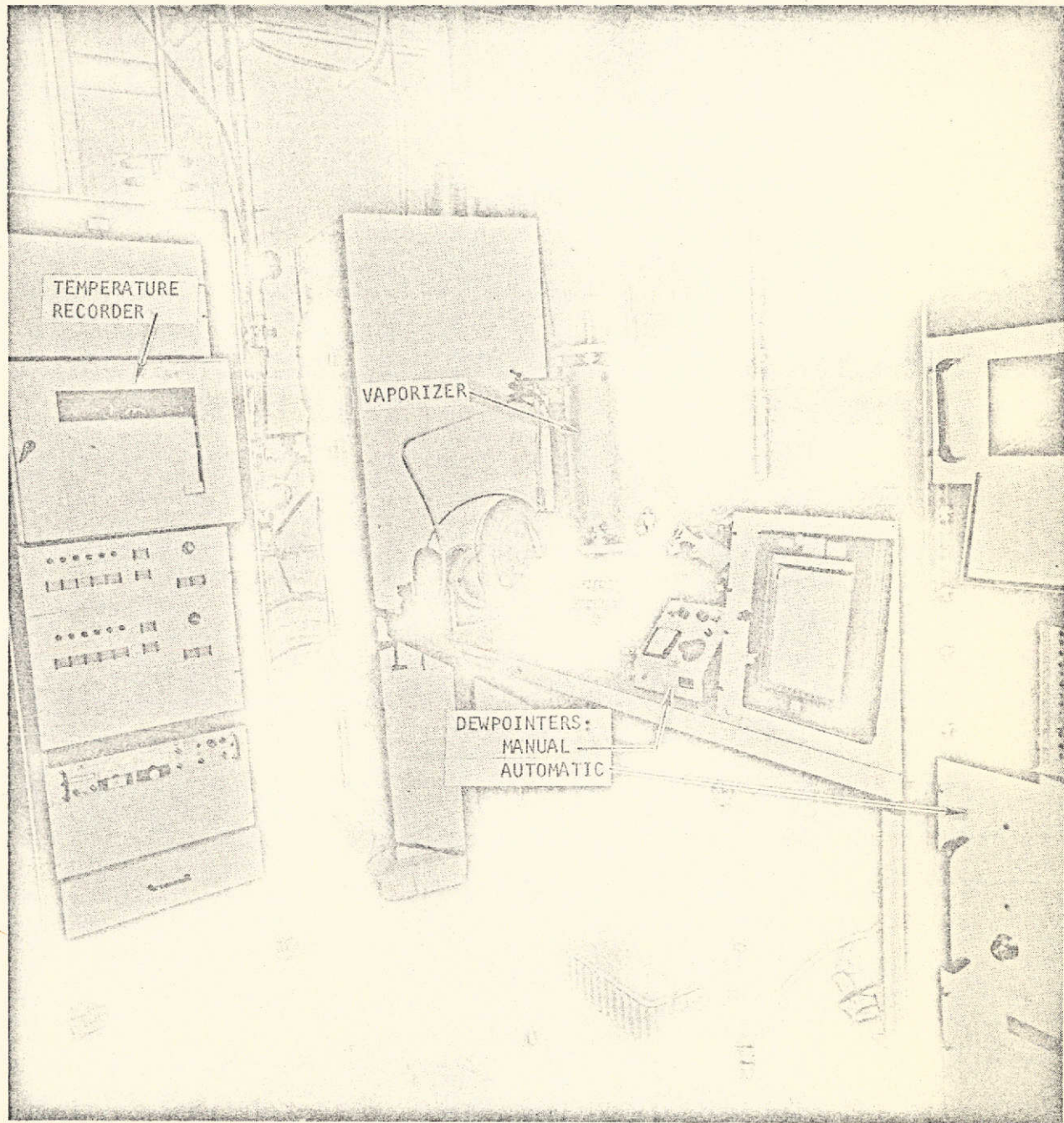


Figure 2-2. Laboratory Test Unit



TABLE 2-2

TEST SETUP COMPONENTS AND FUNCTIONAL DESCRIPTIONS

<u>ITEM NO.</u>	<u>COMPONENT</u>	<u>DESCRIPTION</u>
1	Regulator	Supplies 8 PSIA nitrogen or oxygen to test unit.
2	Flow Valve	Used to adjust flow rate to test unit.
3	Pressure Gauge	Measures outlet pressure or flow meter - used with flow curve. Range 0 - 14.7 PSIA, total accuracy $\pm 0.5\%$ Full Scale.
4	ΔP Gauge	Measures pressure drop across flow meter - used with flow curve. Range 0 - 10 in H ₂ O, total accuracy $\pm 0.5\%$ Full Scale.
5	Vol-0-Flow Gas Flow Meter	Measures inlet flow to test unit. Range 0 - 10 lb/hr, total accuracy $\pm 1\%$ Full Scale.
6	Scales	Measures net quantity of water used to humidify gas. Range 0 to 100 lbs. smallest increment 0.01 lb; accuracy ± 0.01 lb.
7	Dewpoint Heat Exchanger	Adjusts dewpoint of gas to test unit by cooling gas saturated at high temperature to required dewpoint temperature.
8	Dry Bulb Heat Exchanger	Adjusts gas to required dry bulb temperature.
9	Glycol Cart	Circulates refrigerated glycol to dewpoint heat exchanger.
10	Vaporizer	Vaporizes water to saturate gas with water vapor.
11	Variac	Controls amount of heat supplied to vaporizer.
12	Vacuum Pump	Evacuates chamber.



TABLE 2-2 (Continued)

<u>ITEM NO.</u>	<u>COMPONENT</u>	<u>DESCRIPTION</u>
13	Variac	Controls amount of heat supplied to insulated gas lines.
14	Pressure Gauge	Measures inlet and outlet gas pressures to unit. Also used to show pressure at dewpointer. Range 0-14.7 PSIA, $\pm 0.5\%$ accuracy.
15	Cambridge Systems Model 992-C1 Dewpoint Hygrometer	Measures gas dewpoint automatically.
16	Manual Dewpointer	Measure gas dewpoint.
17	Temperature Recorder	24 channel recorder for recording temperatures from thermocouples.
18	Inlet Pressure Gauge	Measures inlet pressure to test unit. Range 0 - 14.7 PSIA, total accuracy $\pm 0.5\%$ Full Scale.
19	ΔP Gauge	Measure pressure drop across test unit. Range 0 - 10 PSIA, $\pm 0.5\%$ PSIA.
20	Thermocouple	Measure test unit inlet temperature. Range 0 - 130°F, accuracy $\pm 1^\circ\text{F}$.
21	Thermocouple	Measure test unit outlet temperature. Range 0 - 130°F, accuracy $\pm 1^\circ\text{F}$.
22	Thermocouple	Measure glycol temperature to dewpoint heat exchanger. Range 0 - 130°F, accuracy $\pm 1^\circ\text{F}$.
23	Thermocouple	Measures cold plate temperature. Range 0 - 130°F, accuracy $\pm 1^\circ\text{F}$.
24	Thermocouple	Measures dewpoint heat exchanger outlet temperature. Range 0 - 130°F, accuracy $\pm 1^\circ\text{F}$.
25	Thermocouple	Measures heater outlet temperature. Range 0 - 130°F, accuracy $\pm 1^\circ\text{F}$.



TABLE 2-2 (Continued)

<u>ITEM NO.</u>	<u>COMPONENT</u>	<u>DESCRIPTION</u>
26	Thermocouple	Measures gas temperature from flow meter. Range 0 - 130°F, accuracy $\pm 1^\circ\text{F}$.
27	Thermocouple	Measures water temperature in vaporizer. Range 0 - 230°F. Accuracy $\pm 1^\circ\text{F}$.
28	Thermocouple	Measures temperature of chamber gas line. Range 0 - 130°F, accuracy $\pm 1^\circ\text{F}$.
29	Thermocouple	Measures temperature of laboratory gas lines to chamber. Range 0 - 130°F, accuracy $\pm 1^\circ\text{F}$.



TEST RESULTS

With the available laboratory unit, the maximum flow rate that could be obtained was approximately 2.5 lb/hr. At this low rate, extreme difficulty was experienced with the test setup in obtaining a constant humidity level in the inlet gas stream, especially at dew points above ambient. The test setup required the use of heated insulated lines and infra-red lamps to prevent condensation. During early checkout tests some preliminary data were obtained, this is shown in Table 2-3. The accuracy of this data is questionable. Before any significant data could be obtained, further testing was halted by NASA direction.

TABLE 2-3
PRELIMINARY DEHUMIDIFIER DATA

Chamber Pressure, mm Hg	Pressure		Temperature*		Flow lb/hr	Dew Point			
	Inlet psia	Outlet psia	Inlet °F	Outlet °F		Inlet °F	psia	Outlet °F	psia
0.52	8.00	6.60	76	80	1.00	64	7.9	4	6.5
0.70	8.00	3.85	75	78	2.00	62	8.0	18	3.8
1.10	8.08	2.08	75	78	2.45	69	8.0	61	2.0

*Due to the low flow rate, gas temperatures were affected by local ambient (including lighting) conditions.

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SECTION 3

MEMBRANE PERFORMANCE ANALYSIS

INTRODUCTION

Permeation through polymeric materials is often assumed to occur by the mechanism of activated diffusion. This model assumes that permeation is basically a three step process. First, the permeating molecules dissolve in the polymer. Second, the molecules diffuse through the polymer. Finally, the molecules come out of solution on the downstream side of the polymeric membrane. The diffusion process is believed to depend on the formation of "holes" in the polymeric network, due to thermal agitation of the chain segments*. The diffusional driving force for this mechanism can be shown to be equal to the chemical potential gradient across the membrane**. For an infinitely dilute solution (of permeant in polymer), the chemical potential gradient is proportional to the concentration gradient.

The solubility of the permeating material in the polymer is assumed to follow Henry's Law, i.e., the concentration is proportional to the partial pressure of the permeating molecules. Thus, the driving force for activated diffusion of dilute solution is proportional to the partial pressure difference in the bulk fluid phases on either side of the polymeric membrane. The direction of permeation is, of course, from the high concentration side to the low concentration side.

It is important to note that the activated diffusion model does not differentiate between "liquid" and "gaseous" diffusion. Once the permeating molecules are absorbed in the polymer network, the molecules are neither liquid nor gas; they exist in the polymer solution phase. The permeant concentration in the polymer is a function only of its partial pressure in the bulk fluid phase; thus the partial pressure is the driving force whether the bulk fluid is liquid or gas. In reality, of course, the solubility of the permeating species may be a function of the total pressure as well as the partial pressure. However, the activated diffusion model does not consider these deviations from Henry's Law.

*A. Lebovitz, Modern Plastics, 43, 139 (1966).

**S. B. Tuwiner, Diffusion and Membrane Technology (Reinhold Publishing Corp., New York City, 1962), p. 38.



In accordance with the above description of the activated diffusion model, the overall permeability coefficient π , is defined as the product of the diffusion coefficient of the permeating species in the polymer D , and the solubility of the species in the polymer S , i.e.;

$$\pi = DS \quad (1)$$

The solubility coefficient is related to the Henry's Law constant k by:

$$S = \frac{\rho_m}{k} \quad (2)$$

where ρ_m is the molar density of the polymer.

Experimentally, the determination of the permeability for given conditions does not involve the use of any mechanistic model; the model is important when extrapolation to other conditions is necessary. In the present work, the assumption is made that the permeability of a given species in a particular polymer is constant. The validity of this assumption varies, of course, with the range of conditions and the particular species - polymer system of interest.

Both the diffusivity and the solubility are actually functions of temperature; thus the permeability is also temperature dependent. Fortunately, the diffusivity usually increases and the solubility usually decreases with increasing temperature, thus mitigating the temperature dependence of the permeability. The solubility can vary with concentration and total pressure. The diffusivity can be greatly concentration dependent, especially with water as the permeating species. The water molecules cause "swelling" of the polymer, allowing the diffusivity to increase with concentration*.

Of course, the activated diffusion model may not fully describe the mass transfer. Continuum or rarefied gas flow may be a significant mechanism, depending on the polymer species (and its pore configuration). Some experimenters have found a total pressure driving force for bulk phase liquid permeation**, thus suggesting the predominance of one of the other flow mechanisms.

*N. N. Li, R. B. Long, and E. J. Henley, I&EC 57, 18 (1965).

**L. B. Ticknor, J. Phys. Chem 62, 1483 (1958), and Elam J., et. al. Membrane Evaporator/Sublimation Investigation, 74-10256, p. 2-6.



The activated diffusion model defines the permeation flux J_i as*.

$$J_i = -\pi_i \frac{d\bar{P}_i}{dr} \quad (3)$$

where \bar{P}_i is the partial pressure of component i and r is the diffusing path length (radially through the tube walls). Equation (3) holds for each diffusing component separately. Axial diffusion has been neglected. The effect of the resistance of the bulk fluid phase is neglected since the diffusion rate in the gas phase is many orders of magnitude greater than the diffusion rate in the polymer phase.

Since the interest is in the concentrations on either side of the membrane, Equation (3) can be written

$$J_i = -\pi_i \frac{\Delta\bar{P}_i}{t} = \frac{-\pi_i (\bar{P}_{i_{in}} - \bar{P}_{i_{shell}})}{t} \quad (4)$$

where t is the membrane wall thickness.

The molar flux can be expressed in terms of the flow rate W_i and mass transfer area A ,

$$J_i = \frac{dW_i}{dA} \quad (5)$$

Therefore,

$$dW_i = \frac{\pi_i (\bar{P}_{i_{in}} - \bar{P}_{i_{shell}})}{t} dA \quad (6)$$

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*S. B. Tuwiner, Diffusion and Membrane Technology (Reinhold Publishing Corp., New York City, 1962), p. 38.



Equation (6) can be written for each diffusing component. The following four assumptions are made in order to solve Equation (6):

- (1) \bar{P} shell is assumed to be constant for each component. This assumption is equivalent to a negligible shell side total pressure drop in both the radial and axial directions.
- (2) The tube side partial pressure ($\bar{P}_{i, in}$) does not vary from tube to tube at a given axial position.
- (3) The tube side total pressure drop in the axial direction (due to flow) is negligible.
- (4) The gas phase follows the ideal gas law.

The tube side partial pressure can be expressed as

$$\bar{P}_{i, in} = x_i P_T = \frac{\bar{W}_i}{W_T} P_T \quad (7)$$

where x_i is the mole fraction of the diffusing component

P_T is the total pressure (constant because of assumption (3) above)

W_T is the total molar flow rate

Equation (6) can be solved by a finite difference approach, i.e.,

$$W_{i, in} = W_{i, out} = \frac{\pi_i}{t} \left(\frac{\bar{W}_i}{W_T} P_T - \bar{P}_{i, shell} \right) \Delta A \quad (8)$$

for each component. The term \bar{W}_i is the average flow rate over the interval ΔA . A computer program has been written to numerically solve Equation (8).

PERFORMANCE OF LABORATORY TEST UNIT

Dehumidification

The physical characteristics of the laboratory test unit were given previously and are:

Tube size, microns	250 O.D. x 200 I.D.
Mean surface area, ft ²	12.2
Number of fibers	9640
Active tube length, inches	6.5



For this initial approximation, the upper value of water permeability and the lower value of nitrogen permeability, reported by Lebovitz* were used (Table 2-1). These values are:

$$\begin{aligned} \pi H_2O &= 10,600 \times 10^{-10} \frac{\text{cm}^3 (\text{STP}) \text{ cm}}{\text{cm}^2 \text{-sec-cm Hg}} \\ \pi N_2 &= 0.16 \times 10^{-10} \frac{\text{cm}^3 (\text{STP}) \text{ cm}}{\text{cm}^2 \text{-sec-cm Hg}} \end{aligned}$$

Figure 3-1 is a plot of the solution to equation (8) for two different inlet dew points and two different shell side pressures. The inlet dew point represents the saturation temperature of the inlet stream while the outlet dew point represents the temperature at which the outlet stream would be saturated with water vapor. Shell side water vapor pressure was assumed equal to total pressure; i.e., shell side nitrogen partial pressure was assumed to be zero. The total flow rate is that at the inlet to the unit, total pressure is 8 psia.

It should be noted that Figure 3-1 assumes a constant tube side pressure. Actually, a significant pressure drop occurred for all three data points shown in Table 2-3. Using the lowest flow rate tested (1 lb/hr) and correcting the dew point (4°F) at the measured pressure (6.5 psia) to 8 psia, yields a corrected outlet dew point of 8°F, which is in general agreement with the calculated value (11°F) shown in Figure 3-1.

Gas Loss

Nitrogen permeation rate through the tube wall is calculated at 3.5×10^{-5} lb/hr. This low nitrogen rate was confirmed by pressurizing the unit to 8 psig (22.7 psia) and submerging the unit in water. No leakage was noted; i.e., no bubble formation was found in one hour.

Gas Side Pressure Drop

The pressure drop for the laboratory unit can be calculated as follows. For isothermal flow in circular pipes, the total pressure drop can be found from the solution of the mechanical energy balance for an ideal gas**

$$\frac{G^2}{g_c} \ln \frac{V_{S2}}{V_{S1}} + \frac{M_m}{2R_g T} (P_2^2 - P_1^2) + \frac{2f G^2 L}{g_c D} = 0 \quad (9)$$

*A. Lebovitz, Modern Plastics, 43, 139 (1966)

**C. O. Bennett and J. E. Myers, Momentum, Heat and Mass Transfer (McGraw Hill Book Co., Inc., New York City, 1962) p. 229



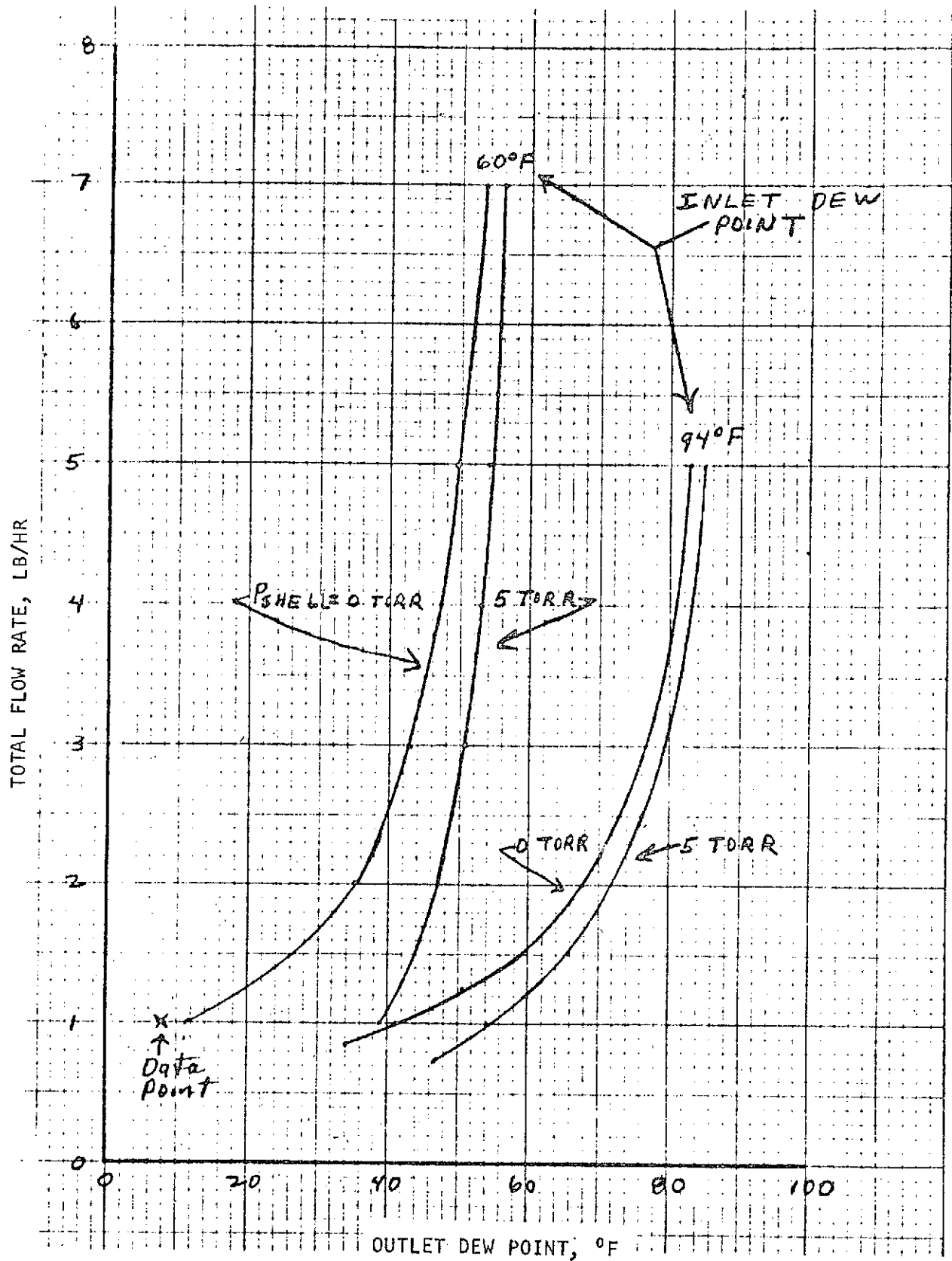


Figure 3-1. Calculated Performance Characteristics
of Laboratory Unit



where G is the mass flux in the tubes (total flow rate divided by cross section area)
 g_c is the gravitational constant
 V_s is the specific volume
 P is the pressure
 T is the temperature
 M_m is the mean molecular weight
 R_G is the gas constant
 f is the friction factor
 L is the flow length
 D is the individual tube inside diameter
 $1, 2$ are the inlet and outlet conditions, respectively.

The flow length is taken as the active length plus 1 inch for header plates, yielding a total flow length of 7.5 in. For a large number of small tubes the flow is laminar for which

$$f = \frac{16}{Re} = \frac{16 \mu}{DG} \quad (10)$$

where Re is the Reynolds number
 μ is the viscosity.

Solving Equations (9) and (10) for a flow temperature of 110°F yields a pressure drop of 0.29 psi for an average flow of 1 lb/hr. For low flow rates, the pressure drop is approximately proportional to the flow rate. The limited data that was taken was with a cellulose acetate unit that was previously used in the evaporator/sublimator testing. This particular unit froze during sublimation tests and afterwards exhibited a much higher pressure drop. In most cases (as with gas inerting units) the calculated pressure drop is significantly higher than actually measured.

FLIGHT UNIT

The test program showed that (1) a cellulose acetate membrane will dehumidify air and (2) the gas loss is negligible. Using the reported permeability value discussed above and equation 8, a preliminary design was made for the dehumidifier problem statement shown in Table 3-1.



TABLE 3-1
DEHUMIDIFIER PROBLEM STATEMENT

Oxygen Loop Parameters	Max. Sustained Heat Load Condition	Min. Heat Load Condition
Inlet Total Flow, lb/hr	16.0	16.0
Pressure, psia	8.0 \pm .15	8.0 \pm .15
Inlet Temperature, °F	110 min.	72 max.
Inlet Dew Point, °F	94	72
Inlet H ₂ O Flow, lb/hr	0.903	0.47 max.
Outlet Temperature and Dew Point, °F	50 max.	35 min.
H ₂ O Condensate Rate, lb/hr	0.728	0.356
Pressure Drop, in. H ₂ O	2.8 max.	2.8 max

In addition, the maximum pressure drop across the dehumidifier will be less than 1.5 inches of water.

The overall configuration is greatly dictated by the low pressure drop required. A preliminary design is shown in Figure 3-2; the more critical design condition is the maximum sustained heat load values shown in Table 3-1. The cellulose acetate hollow fiber membranes are expoxied to a tube end sheet; the end sheets are held by a support tube. This subassembly is slipped into the shell, held in place by a spring and the air plenum module is welded to the shell. Weight of the unit is estimated at 3.2 lb.



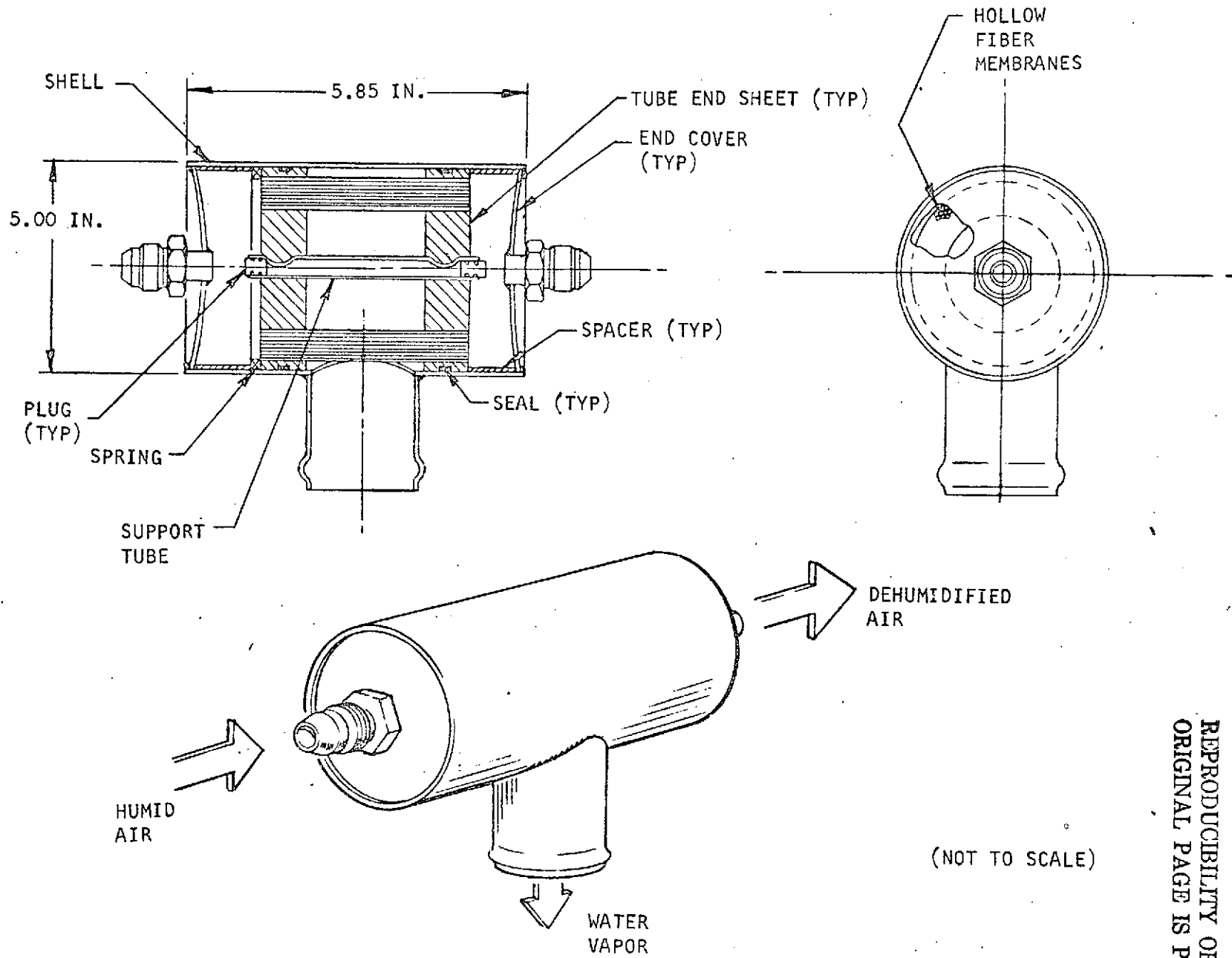


Figure 3-2. Membrane Dehumidifier

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